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14. ABSTRACT
The Lightning Detector instrument, which is part of the VEFI (Vector Electric Field Instrument) on-board the C/NOFS (Communications / Navigation Outage Forecast System) was jointly developed with support from NASA and the National Science Foundation. Once lunched, the Air Force Office of Scientific Research granted the University of Washington the needed support for the scientific analysis of those data to investigate the influence of lightning on the ionospheric plasma. Initially with NASA support, and concluding with this AFOSR grant support, we have prepared the lightning data for public access (see http://cdaweb.gsfc.nasa.gov/istp_public/). This work has quantified the electric field and optical lightning measurements in the ionosphere as never before done. Due to the unique, near equatorial, C/NOFS orbit, practically every orbit passed over active thunderstorms. Results include: observation of lightning transients in the ionospheric electric field above ambient background noise from lightning over 12,000 km from the subttack point; detailed comparison of the optical transient with global lightning source loca

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Final Report
AFOSR Grant FA9550-09-1-0309
Lightning in the Ionosphere with C/NOFS
Principal Investigator: Prof. Robert H. Holzworth
University of Washington
Seattle, WA 98195-1310
8/25/2012

Summary: The Lightning Detector instrument, which is part of the VEFI (Vector Electric Field Instrument) on-board the C/NOFS (Communications / Navigation Outage Forecast System) was jointly developed with support from NASA and the National Science Foundation. Once lunched, the Air Force Office of Scientific Research granted the University of Washington the needed support for the scientific analysis of those data to investigate the influence of lightning on the ionospheric plasma. Initially with NASA support, and concluding with this AFOSR grant support, we have prepared the lightning data for public access (see http://cdaweb.gsfc.nasa.gov/istp_public/). This grant allowed in-depth study of the satellite data, which we combined with ground based lightning location network data, which has resulted in many presentations at national and international science meetings, support for three students in advanced graduate studies, and so far four peer-reviewed scientific journal articles. This work has quantified the electric field and optical lightning measurements in the ionosphere as never before done. Due to the unique, near equatorial, C/NOFS orbit, practically every orbit passed over active thunderstorms. Results include: observation of lightning transients in the ionospheric electric field above ambient background noise from lightning over 12,000 km from the subttack point (more than 1/4 the way around the globe from the spacecraft.); detailed comparison of the optical transient with global lightning source locations and timing of such accuracy that errors in the vehicle clock were detected; report of the close relationship between ionospheric plasma density irregularities and the occurrence of optical lightning activity; and the observation that lightning electric fields were often the largest field inside density cavities caused by the plasma phenomena known as Spread-F.

Lightning Detection from Space: The Instrument.

The VEFI (Vector Electric Field Instrument) on the C/NOFS satellite has been described in de la Beaujardière (2004) (Dr. R. Pfaff, PI). The instrument includes both vector electric field and optical lightning sensors, both of which are necessary for this study of Lightning in the Ionosphere. The optical lightning sensor (LD) was designed by the University of Washington where a flight model of the instrument was built, while the flight version of that instrument built by NASA/GSFC with calibration and testing conducted at the University of Washington.

Figure 1 gives an example of a lightning stroke in the electric field (VEFI) and optical transient (LD) data from C/NOFS.

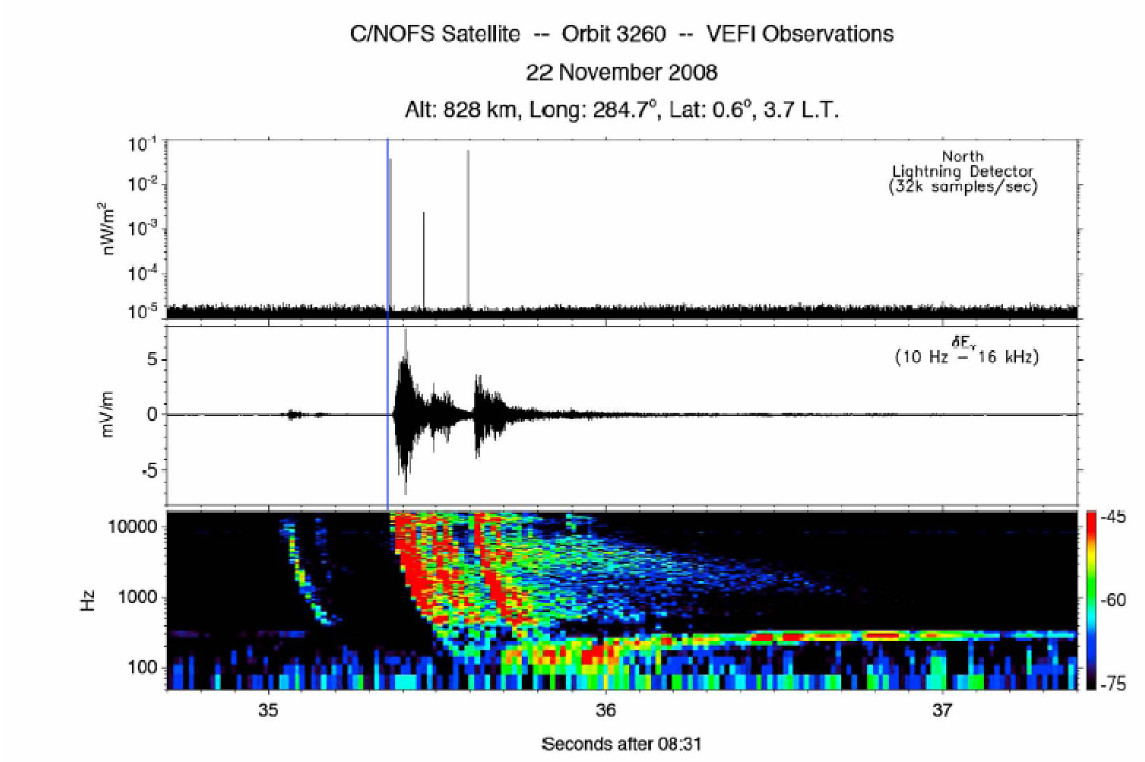

Figure 1. Typical example of three, isolated lightning events from the Optical lightning power (top) and VLF electric field waveform (middle) and spectrogram up to 8 kHz (bottom) during a sample C/NOFS burst mode collection time. Note that the first of three LD optically detected strokes was also located by the WWLLN lightning location network (blue line). (from Holzworth et al, 2011)

The C/NOFS VEFI instrument data collection capability included both continuous and burst mode data. Nearly every orbit included a 12 to 24 second burst of high sample rate waveforms from the wave and/or optical lightning data. For example Figure 2 shows such an burst mode where many lightning transients can be seen in the optical power data (top) and in the electric field spectrogram (bottom).

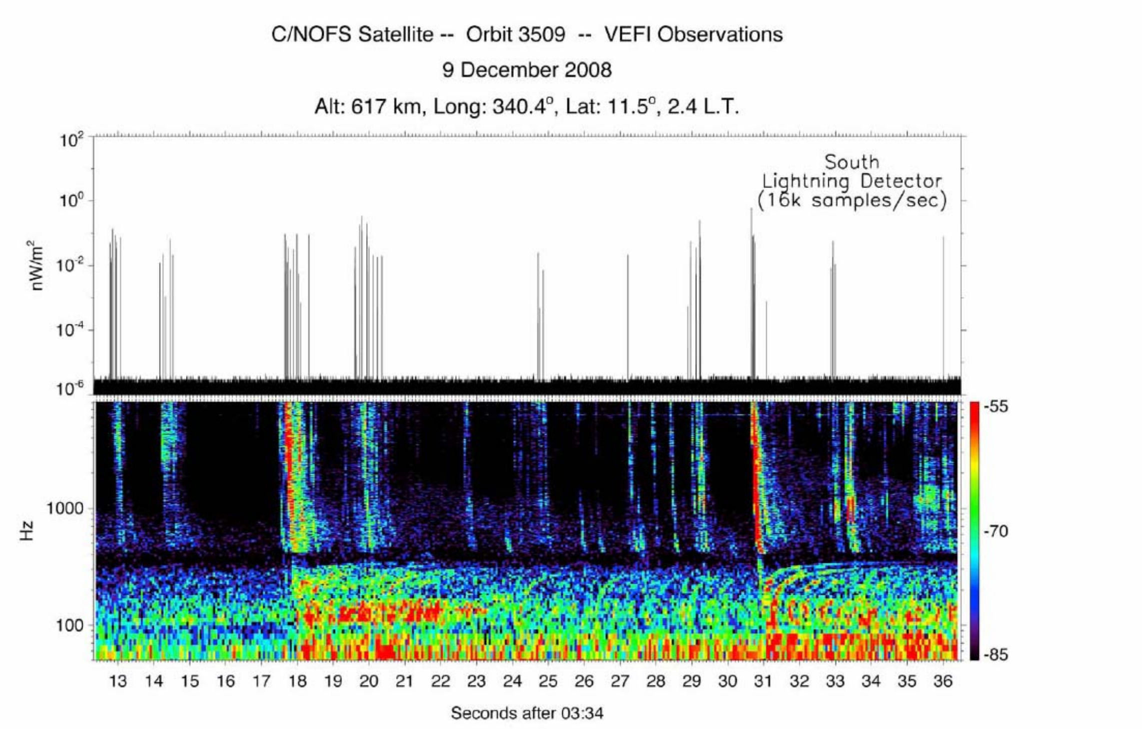

Figure 2. Optical lightning power and VLF electric field spectrogram up to 8 kHz during a sample C/NOFS burst mode collection (from Holzworth et al, 2011)

In Figures 1 and 2 one can see many typical features of the lightning-produced waveform in the top side ionosphere. The most obvious feature is the strong dispersion of the waveform with higher frequencies arriving first at the satellite, followed by the lower frequencies. These dispersed VLF sferics interact strongly with the ionospheric electrons, which have Doppler-shifted cyclotron frequencies in this band. When the lower frequencies arrive they interact strongly with the ions at frequencies below about 500 Hz in this case. Figure 2 shows strong 'ion whistlers' beginning after second 31 in the figure. Also, in Figures 1 and 2, it is clear that these ion whistlers are very strong, and very long lived.(at least a few seconds).

In addition to the high resolution obtained from the burst mode data, as in Figures 1 and 2, the C/NOFS instrument collected optical lightning (LD) data continuously, with counters reading out every 1/2 second, including counts from 7 different optical power levels. Figure 3 gives an example of the longitudinal coverage of the satellite, where the LD data histogram shows the presence of three main regions of lightning as the satellite passes over Africa, Indonesia (and the Maritime Continent) and the Americas.

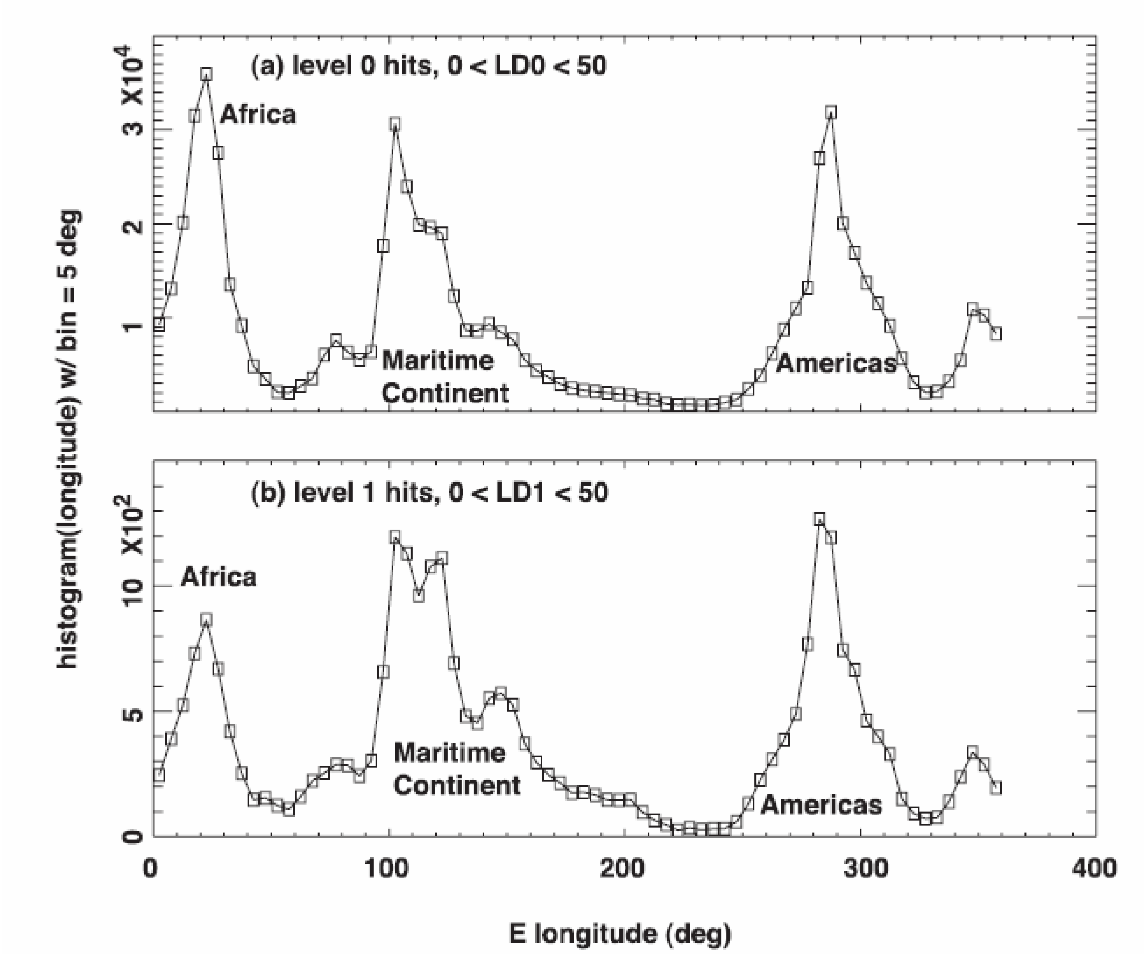

Figure 3. Histogram of lightning events detected by the LD instrument within the C/NOFS VEFI instrument, as a function of longitude. Here the optical lightning events are summed in 5-degree bins. (From Jacobson et al, 2011b)

Scientific Presentations and Publications:

This grant has provided partial support for these scientific paper presentations:

Global Optical Lightning Intensity near the Equator from the C/NOFS Satellite, Reeves, M. C.; Holzworth, R. H.; Jacobson, A. R.; McCarthy, M. P.; Hutchins, M. L.; Pfaff, R. F., American Geophysical Union, Fall Meeting 2010, abstract #AE21B-0277

Optical Lightning Detection and and Vector Electric Field Measurements Gathered in the Low-Latitude Ionosphere by Probes on the C/NOFS Satellite, Holzworth, R. H.; McCarthy, M. P.; Pfaff, R. F.; Rowland, D. E.; Martin, S. C.; Bromund, K. R.; Uribe, P., American Geophysical Union, Fall Meeting 2008, abstract #SA13A-08

Initial Results from the Vector Electric Field Investigation on the C/NOFS Satellite, Pfaff, R.; Rowland, D.; Acuna, M.; Le, G.; Farrell, W.; Holzworth, R.; Wilson, G.; Burke, W.; Freudenreich, H.; Bromund, K.; Liebrecht, C.; Martin, S.; Kujawski,

J.; Uribe, P.; Fourre, R.; McCarthy, M.; Maynard, N.; Berthelier, J.; Steigies, C., American Geophysical Union, Fall Meeting 2008, abstract #SA13A-04

The Vector Electric Field Investigation on the C/NOFS Satellite, Pfaff, R.; Acuna, M.; Kujawski, J.; Fourre, R.; Uribe, P.; Bromund, K.; Hunsaker, F.; Rowland, D.; Farrell, W.; Maynard, N.; Holzworth, R.; Wilson, G.; Berthelier, J.; Steigies, C.; Le, G.; Freudenreich, H.; McCarthy, M.; Martin, S.; Liebrecht, C., American Geophysical Union, Fall Meeting 2008, abstract #SA11A-1483

Equatorial Ionosphere Total Electron Content measurements using whistler waves detected by the C/NOFS Satellite, Willcockson, L.; Holzworth, R. H.; McCarthy, M.; Pfaff, R. F.; Rowland, D. E. American Geophysical Union, Fall Meeting 2009, abstract #SA31A-1408

Observation of Schumann Resonances in the Earth's Ionosphere: Implications for Thunderstorm and Lightning Monitoring from Orbit, Simoes, F.; Pfaff, R. F.; Bromund, K. R.; Freudenreich, H. T.; Holzworth, R. H.; Klenzing, J. H.; Liebrecht, M. C.; Martin, S.; Rowland, D. E.; Uribe, P.; Yokoyama, T. American Geophysical Union, Fall Meeting 2011, abstract #AE21A-0239

On the Relationship between Lightning and Equatorial Ionosphere Density Irregularities, McCarthy, M.; Holzworth, R. H.; Willcockson, L.; Pfaff, R. F.; Rowland, D. E., American Geophysical Union, Fall Meeting 2009, abstract #SA24A-08,

Electron and Ion Whistler Mode Waves Observed in the Low Latitude Ionosphere, Burkholder, B. S.; McCarthy, M. P.; Jacobson, A. R.; Pfaff, R. F.; Holzworth, R. H., American Geophysical Union, Fall Meeting 2010, abstract #SA51B-1632,

In addition this grant has supported the work reported in these papers:

1. Holzworth, R. H., M. P. McCarthy, R. F. Pfaff, A. R. Jacobson, W. L. Willcockson and D. E.Rowland, Lightning-Generated Whistler Waves Observed by Probes on the C/NOFS Satellite at Low Latitudes, J. Geo. Res., 116, A06306, doi:10.1029/ 2010JA016198, 2011
2. Jacobson, A. R., R. H. Holzworth, R. F. Pfaff, and M. P. McCarthy, Study of oblique whistlers in the low-latitude ionosphere, jointly with the C/NOFS satellite and the World-Wide Lightning Location Network, Ann. Geophys., 29, 851-863, doi:10.5194/angeo-29-851-2011,
3. Jacobson, A. R., R. H. Holzworth, M. P. McCarthy, R. F..Pfaff,, Initial studies with the Lightning Detector on the C/NOFS satellite, and cross-validation with WWLLN, Journal of Atmospheric and Oceanic Technology (JTech) DOI: 10.1175/JTECH-D-11-00047.1, V. 28, p. 1423, 2011.
4. Burkholder, B. S. M. L. Hutchins, A. R. Jacobson M. P. McCarthy R. F. Pfaff, R. H. Holzworth, Attenuation of Lightning-Induced Sferics in the Earth-Ionosphere Waveguide and Low-Latitude Ionosphere, JGR? (submitted) 2012.

Scientific Highlights

Large Electric Field Transients in Spread-F Density Cavities

The LD data were instrumental in identifying a possible relationship between the occurrence of lightning and the occurrence of Spread-F caused, deep density dropouts in the ionosphere. Holzworth et al (2011) showed that there is often an apparent, general correlation between regions where ionospheric irregularities occur, and the presence copious lightning activity. Figure 4 shows three orbits of the LD data, along with electric field and density data.

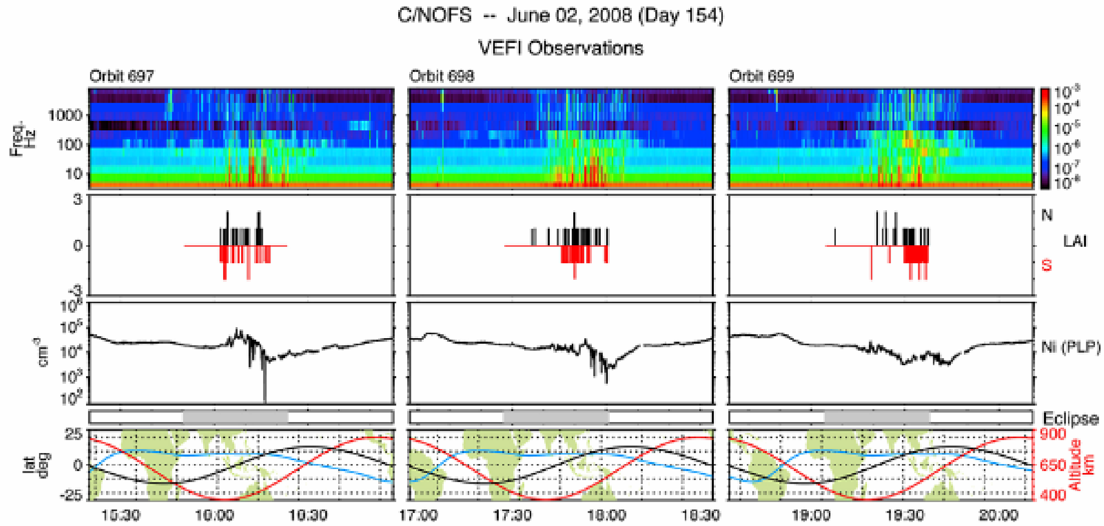

Figure 4. C/NOFS ELF electric field spectrogram (first panel), LD lightning data (second panel), plasma density (third panel), and ephemeris data (fourth panel), showing eclipse periods with shading, along with the altitude and geographic location. (from Holzworth et al, 2011)

The LD data are only available during eclipse periods (see ephemeris on the bottom panel of Figure 4). Looking at the density plot (3rd panels down) one can see that as the satellite repeatedly crosses over the Maritime continent (all three passes) there is an increase in the small and large scale density irregularities, at the same time that the LD instrument (2nd panel) and the electric field spectrogram (top panel) records increasing lightning activity.

This broad correlation required much more careful analysis to determine if the broad agreement between lightning activity and the density perturbations periods were actually closely related, or just coincidentally related. We put the VEFI burst capture program into a mode where the 12 or 24 seconds of high resolution data were triggered upon density dropouts, and found a strong correlation. Figure 5 shows that in the center of these very deep density cavities related to Spread-F plasma instability events, that the electric field bursts from lightning were huge: one to two orders of magnitude larger than ambient ionospheric electric field.

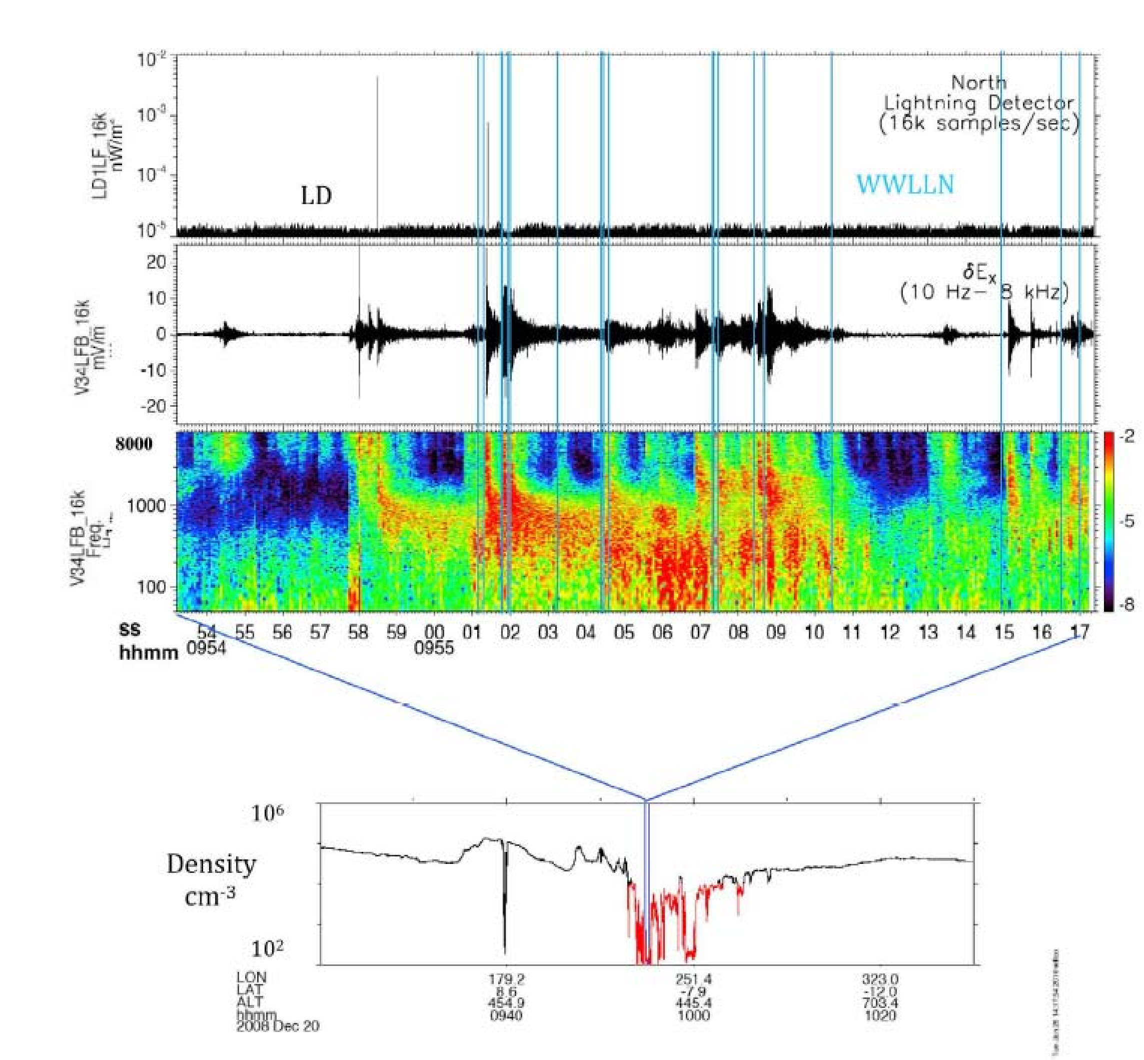

Figure 5. Twenty four seconds of C/NOFS burst mode data during a deep density depletion. The first panel is the LD lightning data. The second panel is the VLF electric field waveform, along with the third panel down which is a spectrogram of the waveform data in the second panel. The fourth panel in the top portion shows the 16 s/sec plasma density data which reveals the very low plasma density associated with the depletion. The large scale series of depletions, in which the data in the four panels are embedded, is shown in the plasma density data in the lowest panel. (from Holzworth et al, 2011)

Lightning VLF Sferic Propagation and Attenuation

An interesting and unique observation made by the VEFI electric field instrument is that there is an East-West difference in the Power seen at C/NOFS in the sferics arriving at the satellite. That is, for lightning that occurs west of the satellite (VLF radiation propagating eastward) the typical amplitudes seen at C/NOFS are SMALLER rather than larger as one might have expected from the sub-ionosphere propagation attenuation. Figure 6 presents a statistical study of this phenomenon.

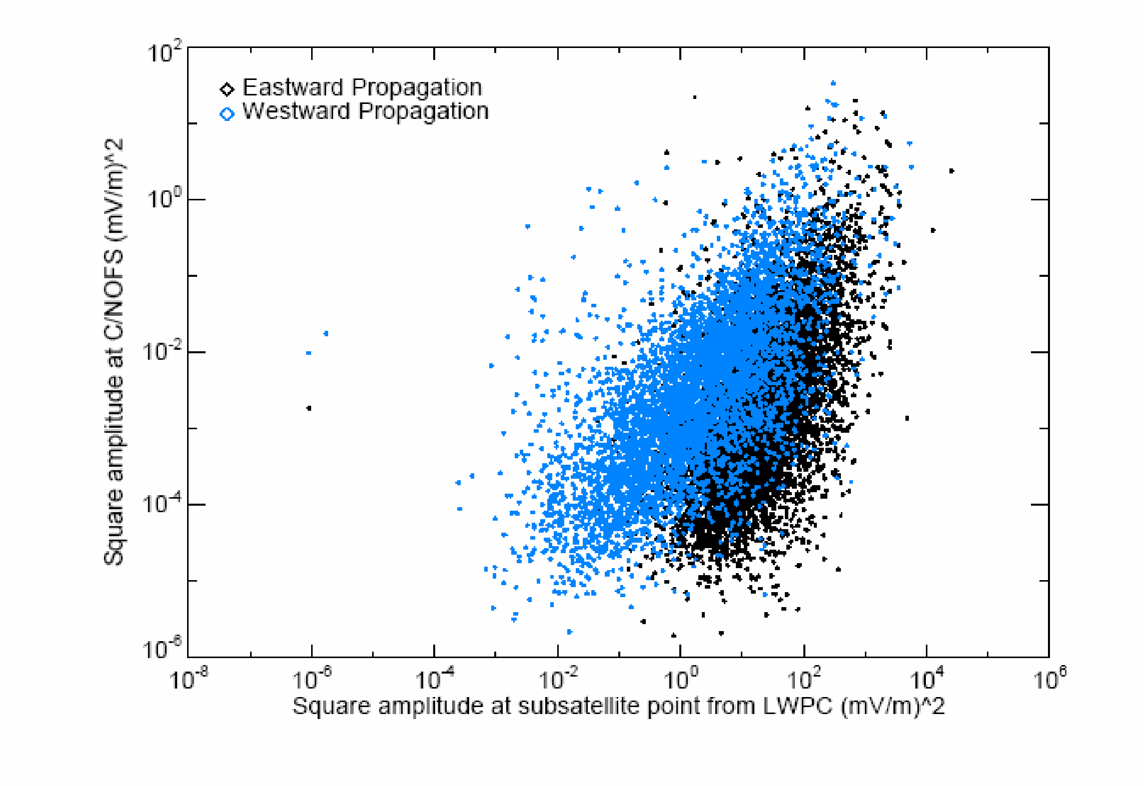

Figure 6. Scatter plot of square amplitude of C/NOFS whistlers versus square amplitude of sferics at the subsatellite point as calculated by LWPC. Data are restricted to those strokes which occurred between 1000 and 8000 km from the subsatellite point, the range in which LWPC produces high quality results. (From Burkholder et al, 2012)

In Figure 6 we plot the amplitude squared of the lightning wave packet (proportional to the electric energy) as a function of the energy of the sferic just below the ionosphere in the earth-ionosphere waveguide. The unexpected feature of this plot is that the typical amplitudes squared from lightning waves propagating to the west (westward propagation, from strokes to the East of the satellite subtrack point) are typically larger than for the waves coming from strokes to the east (that is, westward propagating sferics). This is just opposite of the expected attenuation for VLF waves (see Wait and Sipes, 1960). Indeed, the US NAVY VLF propagation code (the LWPC model, see Ferguson, 1998) shows the well known asymmetry for eastward and westward propagation. Clearly from volumes of research, VLF waves propagating to the west are more strongly attenuated than VLF waves propagating to the east. So, why does C/NOFS see higher average power VLF for lightning wave packets propagating westward? It is shown in this paper that the attenuation for westward propagation can be understood in terms of the reflection and transmission coefficients for subionospheric propagating VLF waves. The attenuation in those westward traveling waves is due to a better coupling upward into plasma whistler waves. So the satellite sees average higher energies from westward propagating waves than for eastward ones. This is the first time a comprehensive study from thousands of events, using both subionospheric VLF wave data at the same time as topside wave data, has been conducted.

Conclusion and Future Work.

The C/NOFS satellite is a goldmine for ionosphere studies of lightning. Prior to C/NOFS we had obtained only a few rocket flights with in-situ vector electric field measurements over thunderstorms. Now with C/NOFS it is like obtaining hundreds of such rocket flights every month. The data set is amazing and continues to be a source for new investigations we have on going at the University of Washington. One of the important next steps will be to quantitatively model the VLF sferic as it penetrates the ionosphere and propagates into the magnetosphere. VLF waves in the magnetosphere are the principle waves which interact strongly with the particle populations. What is the influence of lightning in the magnetosphere? We hope to be able to odirectly address that question with our C/NOFS data and modeling.

Another important future research effort will be to use the C/NOFS data as the orbit decays to lower altitudes, to investigate the actual total energy input from lightning into the D and E region ionosphere.

Bibiography.

Beaujardire, O. de La. C/NOFS: a mission to forecast scintillations. Journal of Atmospheric and Solar-Terrestrial Physics, 66(17):1573{1591, November 2004.

Ferguson, J.A.. Computer programs for assesment of long-wavelength radio communications, version 2.0. Technical report, Space and Naval Warfare Systems Center, 1998.

Burkholder, B. S. M. L. Hutchins, A. R. Jacobson M. P. McCarthy R. F. Pfaff, R. H, Attenuation of Lightning-Induced Sferics in the Earth-Ionosphere Waveguide and Low-Latitude Ionosphere, Radio Science (submitted), 2012

Holzworth, R. H., M. P. McCarthy, R. F. Pfaff, A. R. Jacobson, W. L. Willcockson and D. E.Rowland, Lightning-Generated Whistler Waves Observed by Probes on the C/NOFS Satellite at Low Latitudes, J. Geo. Res., 116, A06306, doi:10.1029/ 2010JA016198, 2011

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Jacobson, A. R., R. H. Holzworth, M. P. McCarthy, R. F..Pfaff,, Initial studies with the Lightning Detector on the C/NOFS satellite, and cross-validation with WWLLN, Journal of Atmospheric and Oceanic Technology (JTech) DOI: 10.1175/JTECH-D-11-00047.1, V. 28, p. 1423, 2011.

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